Agent-based models of animal behaviour

From micro to macro and back.

Ellen Evers, Behavioural Biology, University Utrecht.
Outline

... - genome – cell – organism – group – population – ecosystem - ...

- Organization, structure, patterns
  (spatial, temporal, social, ...)

- Behaviour of animal groups
  (coordination)

- Self-organization
  (complexity arises from simple rules)

- Tool to understand and study: Agent-based Models (ABM)
Flocking examples real: Starlings, ants (movie), fish
Collective motion

- Bird flocks (starlings), insect swarms (flies), mammal herds (wildebeest), fish schools (herring)
Fish schooling

School level:

- **Locomotion:** Simultaneous change of direction
- **Defense:** Flash expansion, fountain effect, aggregation

No disorganized crowd, but *coordinated behaviour* between members of the group!

**HOW** to get structure, patterns, organization in a system?
Organization

Leader:

- Well informed (top-down)
- Provides everyone with instructions
- **No!** Fish change position within school

Blueprint, Recipe, Template:

- Plan or procedure
- Fixed, not very flexible
- **No!** Unlikely in big groups
Fish schooling

Individual level:

- **Vision** (location of neighbours)
- **Lateral line** (orientation of neighbours)

Coordination only with nearest neighbours, whole swarm locomotion through:

SELF-ORGANIZATION!
... process in which a pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. (Camezine et al, 2001)

- No external, centralized control (no leader)
- Local information, simple rules (no global plan, overview)
- ORGANIZATION! (bottom-up)

FISH SCHOOLING? COLLECTIVE MOTION?
Fish schooling

Self-Organization Hypothesis:
Few simple rules in response to local information from neighbouring fish generate schooling patterns without directly coding for them. (Huth & Wissel, 1992)

Schooling rules:
1. Cohesion
2. Separation
3. Alignment
Fish schooling

Self-Organization Hypothesis:
Few simple rules in response to local information from neighbouring fish generate schooling patterns without directly coding for them. (Huth & Wissel, 1992)

To test hypothesis and understand mechanism:

Models?!

Agent-Based Models (ABM)
Models

What is a model?
Models

BUCHAREST SUBWAY MAP

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Models
Models
Models
Models

Definition:

Representation of a system of entities, phenomena, or processes
to simplify, visualize, simulate, manipulate and gain intuition about the entity, phenomenon or process being represented.

Simplification versus Realism
Collective motion

Model rules:

1. Cohesion
2. Separation
3. Alignment

Craig Reynolds 1987: **bird flocking** (*BOIDS*)
Huth & Wissel 1992: **fish schooling**

Hooper, 1999: **predator avoidance** (*cool school*)
Collective motion

Conclusions from the model:

- **Simple rules** can account for **complex pattern**
- **No leader**, no external cue necessary
- Schools could be **self-organizing**

- No proof of real mechanism
- Proven: possible explanation works
2nd part
Scientific models

AGENT-BASED MODELS (ABM)

ORDINARY DIFFERENTIAL EQUATIONS (ODE)

Spatial
deterministic
monte carlo simulation
partial differential equations
complex system
difference equation
cellular automata

Spatial
ordinary differential equations
CA
nonlinear
dynamical
static probabilistic
IBM
ODE
IOM
PDE

AGENT-BASED MODELS
(ABM)

ORDINARY
DIFFERENTIAL EQUATIONS
(ODE)
Predator-prey system

a) data:

b) model:
ODE:

- Population densities

ABM:

- Discrete individuals
ODE:

- Equations

\[
\begin{align*}
\frac{dS}{dt} &= bS - pSW \\
\frac{dW}{dt} &= pSW - dW
\end{align*}
\]

ABM:

- Rules (if-then, loop, scheduling)

**SHEEP:**
If I meet **wolve**: die!
With chance = birthrate: Reproduce!

**WOLVES:**
If I meet **sheep**: energy +1
If energy (from **sheep**) = 0: die!
With chance = birthrate: Reproduce!
ODE:
- Deterministic

ABM:
- Stochasticity (pseudo-random numbers)
  ... to represent variability of processes that **cannot** or **need not** to be modelled deterministically

After Grimm 2005
ODE:
- Non-spatial
- Homogenity
- Well mixed

ABM:
- Explicitly spatial
- Heterogeneity
- Local interactions (bottom-up, adaptive)
- Patterns
ODE:
- Homogeneous population

ABM:
- Individual variation (age, colour, knowledge, spatial position, size, sex, ...)

Sheep
Wolves
Agent-based Models

= Agent-based Models (ABM)
= Individual-based Models (IBM)
= Individual-oriented Models (IOM)

... describe **behaviour, variability** and **interactions** of autonomous individuals.

After Grimm 2005
Collective foraging

- Ants: Trail formation, transporter recruitment, efficient path finding, PHEROMONES!
Collective foraging

Collective decision of colony:

- Selection of richest of two foods
- Selection of shortest path

- Hyp 1: directed by leader (queen?)
- Hyp 2: **Self-organization**

- **Global** pattern **emerges** from simple rules and **local** information
Collective foraging

Foraging rules:

- Execute random walk or follow strongest pheromone trail
- Food found: walk home & leave pheromone trace

Collective foraging

Self-organization:

- Simple rules
- No global knowledge, local information
- Self-reinforcing phermone trails
- Feedback via environment

**Emergence** of accurate (not perfect!) collective decision: efficient path selection.
Self-organization

Mechanism:

- Information from neighbours
- Information from local environment (stigmergy)

- Feedback from emerging structure (control, signal)
Emergent properties

... arise out of interactions between lower-level entities, yet are *novel* and *irreducible* to them.

(Stanford Encyclopedia of Philosophy)

**Emergent property:**
Order, organization, pattern on group level

**Entities:**
Individuals without global knowledge, plan or intent
Emergence

- Self-organization

- Complex Systems
  - physical and chemical systems (liquid)
  - biological systems (cell, brain)
  - social systems and organizations (stock market, social structures)

Complex system patterns often emerge through self-organization.
Complex Systems

Multiple levels of organization!

- Individual < subgroup < population
- Interconnected, interdependent
- Higher level affects lower one
- Higher level has “behaviour” on its own

- Emergent property: Substrate to evolution
3rd part
ABM in science?

Criticism:

- Too complex to be understood
- Impossible to include everything in a model
- Too many parameters unknown
- Hard to test
- Parameters can tweak everything
- “Gaming”
Modelling cycle

- Communicate the model
- Formulate the question
- Assemble hypotheses
- Chose model structure
- Implement the model
- Analyze the model

Patterns!
Modelling cycle

Formulate the question:

- Filter for essential processes
- Not model per se, but for specific purpose
Modelling cycle

Assemble hypotheses:

- Starting point: conceptual model (drawing)
- Based on empirical data, experience, theory, gut feeling

- What do we expect to see? **PATTERNS** (at multiple levels)
Modelling cycle

**Chose model structure:**

- Which entities?
- Which processes?
- How to model/represent processes?
Modelling cycle

**Implement model:**

- Write program code (if-then rules, loops)
Modelling cycle

Analyse the model I:

- Controlled simulation experiments
  (visual debugging, process understanding, extreme tests)

- Design and analysis just as with “real” experiments
  (statistics on program generated data)
Modelling cycle

Analyze the model II:

- Much freedom and control in experimental setup (upscale numbers and time, hypothetical thought experiments)

- Can the model reproduce **PATTERNS?** (at multiple levels!!!)
Modelling cycle

Analyze the model IIIa:

- Change parameter/rule: Effect on system behaviour? (knockout, sufficient & neccessary)
Modelling cycle

Analyze the model IIIb:

- Multiple runs, same parameter set (account for stochasticity)
Modelling cycle

Communicate the model:

- Materials & Methods
- Reproducability of results
ABM – a scientific method

Model validation:

- New hypotheses from the model
- Not built into the model beforehand
- Can be tested in “real” system

After Grimm 2005
Primate social cognition

- Social structure: dominance hierarchy
- Spatial structure: centrality of dominants
Primate social cognition

- *DOMWORLD* (Hemelrijk 1999, Hogeweg 1988)
- Simple rules $>$ complex behaviour

1. Grouping rules:

- Max view
- Near view
- Personal space
Primate social cognition

2. Interaction rules:

- Prediction
  (mental simulation)

- Dominance contest:
  - Win chance \( \sim \) rank
  - Loser flees, winner chases

- *Dom*-value **update** according to expected outcome
  (winner-loser effect)
Primate social cognition

- Dominance hierarchy
  (differentiation from initially equal individuals)
  (individual variation!!)

- Emergence of spatial structure
  (centrality of dominant individuals as unintentional side-effect)

- Stabilizing feedback from spatial structure on social structure:
  - neighbors of similar rank
  - no unexpected outcomes
  - no big updates of dom-value

Hemelrijk, 1998
Primate social cognition

INSIGHTS:

- No centripetal instinct necessary for spatial structure
- From side effect to evolutionary substrate
- Emerging spatial structure feeds back on social structure

ABM internship: http://bio.uu.nl/behaviour/people/Evers/index.html
Evolution *in silico*

**Evolution ingredients:**

- **Mutations:**
  - Inheritance of traits (to offspring)
  - Chance of changing traits

- **Selection:**
  - Define fitness measure
  - Explicit selection
    (once in a while: take out 100 best and reproduce)
  - Reproduction/death
    (dependent on fitness measure)
Conclusions

**Biological systems:**

- Organisation / patterns

**Several possibilities:**

- Central, fixed control (leader, blueprint, ...)
- Self-organisation
  - Interactions between individuals
  - Emergence of pattern on group level
Conclusions

**ABM: useful tool to study / understand**

- Multiple connected levels *(individual, group)*
- Behavioural rules

- Explicit spatiality:
  - Locality
  - Heterogenous space

- Individual variation *(hierarchy, evolution)*

**Heraklit:** You never enter the same river twice.
Conclusions

Models are useful:

- **Development:** Explicit formulation of processes
- **Simplification:** Identify essential (sufficient & necessary) processes

- **Scientific research tool:**
  - Controlled experiments (*knockout*, change parameter/rule)
  - Series of runs (variation)
  - Statistics on generated data
  - Material & methods
  - Reproduced results: validation
Conclusions

Models advantages:

- Freedom in experimental setup
- Little time, money, animals, facilities needed
- No ethical objections

- Generate new hypotheses
- Reveal general and unexpected properties of a system
- Help understanding a system
- Change way of thinking about a system

Proust: The real voyage of discovery lies not in finding new landscapes, but in having new eyes.
Sources

**Modelling, general**


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Agent-based models of animal behaviour


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